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The broadband electromagnetic sensor improvement and demonstration undertaken in this project took the prototype GEM-3 and evolved it into an operational sensor with increased bandwidth and dynamic range, and enough memory and processing power to allow efficient data acquisition while decreasing the weight for ease of operation. In addition to the original hand-held configuration specified at the outset, a cart-mounted large-coil configuration has also been developed for surveying large open areas. Specifically, the frequency range was doubled from 24 kHz to 48 kHz, 24-bit ADC replaced the 16-bit ADC providing 48 dB increased dynamic range, digital signal processor fast enough to allow continuous operation at more than 10 frequencies simultaneously, and compact-flash memory accommodating internal storage of a days surveying.

Other new capabilities include real-time output of data for logging into a portable computer (either laptop or palm) as an option to internal storage. Seamless integration with GPS provides geo-referenced data in UTM grid coordinates. Utility software for both the laptop and the palm computers provide an advanced user interface for configuring and controlling the GEM as well as real-time data display and processing. Mechanical construction was refined as well.

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List of Acronyms

Analog-to-Digital Converter	ADC
Aberdeen Proving Ground	APG
Differential Global Positioning System	DGPS
Digital Signal Processor	DSP
Electromagnetic Induction	EMI
Electromagnetic Induction Spectroscopy	EMIS
False Alarm Rate	FAR
Field Effect Transistor	FET
Probability of Detection	PD
Receiver Operator Characteristics	ROC
Receiver coil	Rx
Signal-to-noise ratio	s/n
Transmitter coils	Tx
Unexploded Ordnance	UXO

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ABSTRACT

The broadband electromagnetic sensor improvement and demonstration undertaken in this project took the prototype GEM-3 and evolved it into an operational sensor with increased bandwidth and dynamic range, and enough memory and processing power to allow efficient data acquisition while decreasing the weight for ease of operation. In addition to the original hand-held configuration specified at the outset, a cart-mounted large-coil configuration has also been developed for surveying large open areas. Specifically, the frequency range was doubled from 24 kHz to 48 kHz, 24-bit ADC replaced the 16-bit ADC providing 48 dB increased dynamic range, digital signal processor fast enough to allow continuous operation at more than 10 frequencies simultaneously, and compact-flash memory accommodating internal storage of a days surveying.

Other new capabilities include real-time output of data for logging into a portable computer (either laptop or palm) as an option to internal storage. Seamless integration with GPS provides geo-referenced data in UTM grid coordinates. Utility software for both the laptop and the palm computers provide an advanced user interface for configuring and controlling the GEM as well as real-time data display and processing. Mechanical construction was refined as well.

The technology demonstration scope was all encompassing, including blind-grid testing of three configurations – hand-held 40 cm sensor, pushcart mounted 96 cm sensor, and ATV towed 96 cm sensor, challenge scenarios – woods and moguls using the hand-held sensor, and large open field using the large coil with pushcart and towed configurations. The moguls area was covered with snow, the woods and parts of the open area with several inches of water.

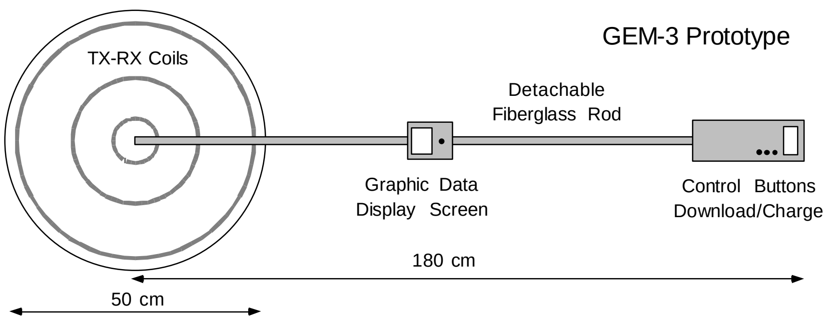
The results of the demonstration indicate a need for further work. Performance in the moguls and woods was not consistent with our other experiences with detection capability of the hand-held GEM-3, and we believe a problem with our target geo-referencing may have occurred. Detection performance was more reasonable in the other areas, but discrimination capability has yet to be realized. Further system improvements that may help accomplish this include increased range capability for detection of deeper targets, and improved detection channel algorithms and discrimination algorithms. Acquisition methodologies also must be improved; ensure the geo-referencing is correct, and improve the cart and towing platforms and ATV navigation.

1. Introduction

1.1 Background

The environmental problem addressed by this project is the need to clear areas of UXO contamination in order to reclaim former DoD practice ranges and weapons test sites for non-military use. This program is directed at the task of detecting and distinguishing from non-ordnance clutter buried UXO in a cost effective method.

The main objective of this project is to build and demonstrate an improved broadband GEM-3 electromagnetic induction (EMI) sensor for UXO detection and discrimination. The GEM-3 sensor concept was implemented in a prototype as described by Won *et al*, 1997, with the major innovative design features consisting of a concentric coil configuration (co-located transmitter and receiver coil centers, referred to as monostatic, schematic shown in Figure 1) with a secondary ("bucking") transmitter coil that creates a primary magnetic field cavity around the receiver coil, and a fully digital electronics architecture allowing user-selectable multiple frequencies to be recorded simultaneously. The magnetic field cavity reduces the dynamic range requirement by removing the primary field, permitting receiver sensitivity high enough to resolve weak fields from a target while operating in a continuous wave frequency-domain mode.



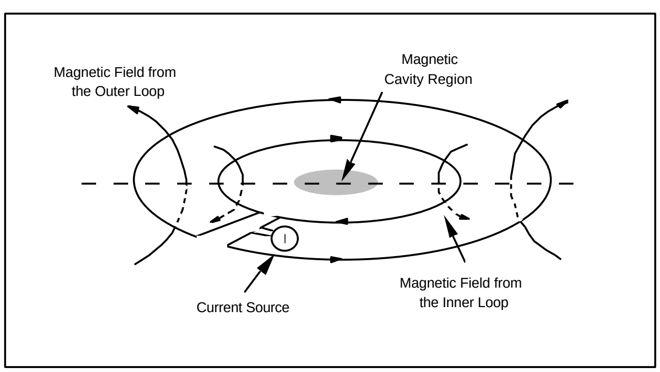


Figure 1. Schematic of the GEM-3 (top), and conceptual representation of the GEM-3 coils (bottom) creating a central magnetic cavity region using two concentric, circular loops that are electrically connected in an opposing polarity.

The receiver coil measures the perturbations of the magnetic field from nearby conductive and/or magnetically permeable objects (particularly metal); the perturbations are "normalized" by a reference coil near the transmitter that measures the primary field, and the output signal is in complex dimensionless units of parts-per-million (ppm) of the primary field that would be measured if there were no "bucking" transmitter coil – the inphase and quadrature ppm spectral components are the real and imaginary parts phase referenced to the reference coil.

We completed the new sensor hardware by the end of 2001 and, since then, have made minor hardware upgrades and have been continuously improving and testing the sensor software. The advantage of this technology over conventional EMI or magnetic sensor technology is the potential for target characterization using the broadband multi-frequency capability.

The GEM-3 sensor consists of a sensing head and an electronic console for real-time data processing. The console digital signal processor (DSP) performs the transmitter waveform generation, receiver analog-to-digital converter (ADC), convolution math (digital Fourier transform at operational frequencies) to produce inphase and quadrature at each frequency, and data logging for multiple channels including a differential global positioning system (DGPS) with a real-time clock. Major improvements under this project include the following:

- Higher maximum transmitter moment (from 6A to 12A, 40A with high-power option)
- Higher transmitter waveform resolution (from 96kHz to 1,536kHz)
- Improved receiver – ADC from 48kHz @ 16bits to 96kHz @ 24 bits
- Increased computing power and faster data collection – fully 30 times a second up to 15 frequencies
- Advanced display (visual and audio) – a bigger screen
- Data-logging function – other data including GPS navigation data
- Increased number of frequencies for detection survey, and
- Integration of a real-time detection/discrimination algorithm (for hand-held operation).

The gain in signal–to-noise ratio (s/n) from the increase in maximum transmitter current depends on several factors. Although the maximum current sustainable by the electronics is doubled, the actual realized increase depends on the set of frequencies chosen – high frequencies are inductively loaded and demand a greater share of the available (12 volt) voltage, and using more frequencies shares the voltage and decreases the peak current. With a ten frequency hybrid waveform spread roughly logarithmically over the sensor 48 kHz band (typical), the current will not reach 12 A, but if the selection is restricted to a few frequencies at the low end, the maximum current will be attained and the benefit more clear cut.

The GEM-3 transmitter current is produced by computer controlled rapid switching of the full battery voltage into the transmitter coils, with a current response characterized by the natural self-inductance and resistance of the coil. The pulse-train pattern is customized to deliver current at the user-selected frequencies. The higher transmitter waveform speed offers a more power efficient transmitter system because a lower speed (also implies longer duration pulses) results in more current overshoots that must be countered with current pulses of opposite polarity, and thus more power expended at (non-operational) switching frequency. Also, a slower waveform pulse train with longer pulses results in higher primary field spikes, which consumes much of the receiver dynamic range with residual (bucking error) primary field induced voltage.

The increase in sampling rate to 30 Hz (with an option to average internally, reducing the output rate but narrowing the noise bandwidth around each operational frequency) provides a clear-cut increase in spatial resolution during survey mode operation and greater stacking rate for s/n improvement during static logging over a target.

The 24-bit ADC provided much needed dynamic range without sacrificing sensitivity. In our early systems using a 16-bit ADC, we had experienced problems with sensor saturation in magnetic terrain, notably Kaho'olawe, as well as the road lanes at the landmine test site at Aberdeen Proving Grounds. In an early test at Kaho'olawe, it was necessary to reduce the electronics gain, thereby reducing sensitivity, in order to operate. At the APG mine lanes, we abandoned testing on the road lanes and could only operate over the off-road (grass) lanes. Large shallow metal targets can also saturate the ADC, and the 16-bit version had a much lower threshold before this limitation was reached. The doubling of the ADC speed to 96 kHz doubled the operational bandwidth to 48 kHz (we are now moving to 182 kHz sampling for 96 kHz bandwidth). Many targets have not reached the inductive limit at 24 kHz, i.e. the spectral character is not completely defined below 24 kHz, so the added bandwidth should enhance spectral based discrimination.

The advanced display has been superceded by integration with a palm-held computer (e.g. iPAC).

The data logging function allows tight integration of auxiliary data with the GEM data; the primary application thus far has been DGPS, but it could include magnetometer data or other sensors that utilize an RS-232 output.

The maximum number of frequencies goes hand-in-hand with the increased bandwidth; in order to take advantage of the bandwidth without sacrificing spectral resolution, more frequencies are needed. Also, increasing spectral resolution should enhance target discrimination based on spectral character, particularly when several different types of targets are of interest.

Integration of real-time detection (audio enunciated) and discrimination provides an operational prototype of an advanced system for locating targets and prioritizing a dig decision on the spot. Currently we have implemented a simple single-point spectral matching based algorithm (best-fitting linear combination of axial and transverse target orientation frequency responses). More advanced schemes using multiple spatial samples could be added.

1.2 Objectives of the Demonstration

Through this program, the GEM-3 has evolved from prototype into a fully operational (full-scale) instrument, and the objective of this demonstration was to verify its capability to perform under realistic conditions of buried UXO contamination. The goal is to combine multi-frequency inphase and quadrature data in an optimal way to identify local anomalies that are potentially UXO.

The GEM-3 may be used in two versions, handheld with either 20 cm or 32 cm radius sensor (20 cm for this demonstration), or cart/sled-mounted with 48 cm sensor, as shown in Figure 2. The large-disk configuration can be mounted on a PVC sled and towed with an All Terrain Vehicle (ATV), or mounted on wheels and hand-pushed where greater maneuverability is required. The GEM-3 electronics has integrated DGPS navigation capabilities, although, for this demonstration, we flagged anomalies when using the hand-held sensor and located them with a stand-alone DGPS afterwards.

Figure 2. The GEM-3 can be either handheld, or cart/sled-mounted and pushed or towed

The first phase GEM-3 demonstration was performed at the Kaho'olawe, Hawaii test site, and the final phase at the Standardized UXO Technology Demonstration Site in the Aberdeen Proving Ground (APG), located in Harford County, Maryland between Philadelphia and Baltimore. The Kaho'olawe site includes several 30 m x 30 m calibration grids and 22 blind grids also 30 m x 30 m each, of varying (moderate – high) geologically magnetic terrain; the demonstration phase at that site was performed in October 2001. The APG site includes (1) Calibration Lanes, (2) Blind Test Grid, (3) Open Field, (4) Moguls, and (5) Wooded Area. The Moguls area was completed during December 2002, but because of excessive snow cover, surveying the remaining areas was postponed until April 2003.

At Kaho'olawe, we used the cart-mounted 48 cm disk exclusively, with integrated DGPS positioning of survey data recorded by the GEM-3 electronics. At APG, we used both the 20cm disk hand-held version and the 48cm cart/sled-mounted GEM-3 during this demonstration and tested their buried UXO detection and discrimination performances; the cart/sled-mounted configuration was used where the terrain and vegetation conditions allow (open field), and the handheld configuration in heavily wooded, overgrown, or rough areas (wooded and mogul areas). Most of the Open Field (about 70%) was surveyed using the sled towed by the ATV, but the pushcart was used in small sections where lines were short and turning space limited.

The objective of the demonstration is to evaluate both the GEM-3 hardware as well as the data processing, including detection and discrimination algorithms. We have available the following detection algorithms:

- **Quadrature Sum**: sum of multi-frequency quadrature responses, which are insensitive to geologic magnetic susceptibility, weakly sensitive to geologic conductivity.

- **Inphase Difference:** difference between high and low frequency inphase desensitizes to geologic magnetic susceptibility, can choose frequencies with less noise as long as they are separated enough to show adequate response change for all targets of interest (typically a decade or more) relative to noise envelope. The optimum is to pick the greatest frequency spread while avoiding a markedly noisier frequency.

- **Spread Functions (Quadrature or Inphase):** sum of absolute differences among all chosen frequencies, best at suppressing geologic noise, but random (high spatial frequency) noise increases

- **Total Apparent Conductivity:** non-linear transformation tends to bring out weaker anomalies (small or deep UXO), weighted average over all frequencies, 1/log(f) weighting which favors metal over geology.

In all of these algorithms, a preview of the individual spectral components, or comparing results (i.e. resultant map clarity – somewhat subjective), allows exclusion of problem frequencies. For the survey mode data (cart or towed), since the algorithms are performed in post-processing, maps from various choices can be compared. In practice, frequencies below 270 Hz are often degraded by platform motion for a cart mounted system, and the highest frequency, near the system band limit, is often noisier than the others, and is more sensitive to conductive soil as well. The 90 Hz and 150 Hz and 47970 Hz were excluded in the detection channel (Qspread) at Kaho'olawe and the lowest (90 Hz) and highest (41010 Hz) at APG for the total apparent conductivity. In hand-held operation, the benign platform dynamics allowed use of all frequencies at APG.

These algorithms provide a means to combine multi-frequency data into a single output measurement that is used as the Response Stage of the Demonstration Submittals (dig lists). They also drive sound and graphical display signals to the operator for real-time detection of EMI anomalies that may indicate buried UXO, or anomaly-picking criteria in the automated target picking software used in survey data post-processing.

At Kaho'olawe, we used primarily the quadrature spread for its ability to suppress magnetic geologic responses (at that time, we had not yet implemented the total apparent conductivity), and targets were picked manually and processed one-by-one for discrimination. The total apparent conductivity is considered the overall optimum Response Stage and was used for the Open Field at APG, in which the survey data were post-processed in batch mode. Real-time implementation at that time required the use of the simpler Quadrature Sum in the hand-held configuration in which the operator picked targets during the survey.

For discrimination, we applied library-based spectral identification procedures we have developed using Electromagnetic Induction Spectroscopy (EMIS), described in more detail below. The confidence value for the Kaho'olawe submittals was assigned by the data processor based on the weighted global misfit from multiple spatial positions, factoring in (subjectively) features such as the spatial variation of the response. At APG, the Discrimination Stage was computed from the matching misfit, where we mapped zero fitting error to a maximum value of 10 and infinite fitting error to zero via the form:

$$DS = C/(0.1*C + Error)$$, with C chosen to obtain the desired DS distribution.

The motivation for this equation is to generate a confidence rank (called Discrimination Stage by ATC) from 1 to 10 with increasing values corresponding to higher confidence that the item is UXO (higher dig priority). The algorithm used to classify/rank depends on a misfit between the measured spectra and the best fitting spectra stored in a training library of potential UXO. The raw misfit can be essentially zero (perfect match) to a very large (no theoretical limit) misfit, with smaller misfit corresponding to higher confidence that the target is UXO. The above equation inverts the low-high character and bounds the values between 0 and 10 as desired, and the "C" coefficient is the misfit threshold considered best estimate of division between UXO (misfit below C) and clutter (misfit above C); the threshold is mapped into a Discrimination Stage value of 5, the midpoint of the range.

We set the value of C to 8 for the APG testing, derived at subjectively from testing in the calibration grid, and from obtaining what we thought was a reasonable fraction of targets declared UXO. This latter point is highly speculative, but at this point we do not have sufficient experience with the range of targets and conditions encountered at APG to know what the optimal value would be. By creating ROC curves, in principle, we hope to learn what the best value is.

1.3 Regulatory Drivers/DoD Directives

This program was undertaken in response to the ESTCP Topic 1: Unexploded Ordnance (UXO) Detection, Discrimination, and Remediation.

1.4 Stakeholder/End-User Issues

This demonstration will address decision-making issues concerning end-users associated with the applicability of the GEM-3 technology for their specific UXO detection and discrimination mission needs. Operational performance under a variety of conditions will be assessed, including production capabilities, field usability, and logistical requirements. Both hand-held (with small sensor disk) and cart/sled-mounted (large sensor disk) configurations were evaluated, providing end-user assessment of the performance and operational usability of each.

2. Technology Description

2.1 Technology Development and Application

2.1.1 Hardware

The GEM-3 EMI system consists of three basic components: the monostatic coil sensor, the electronics console, and the user interface (control and display) module (Figure 2). This functional architecture, as well as the essential features of the sensor coils and electronics, have not changed since the original prototype, as described by Won *et al*, 1997. The key innovation is the concentric coil configuration, in which the receiver coil (Rx) is the innermost coil, located in a region of a primary magnetic-field cavity produced by a pair of transmitter coils (Tx) configured so that the current in the inner (bucking) Tx flows in the opposite direction as the outer (primary) Tx (Figure 2). The number of turns in the primary coil is double that in the bucking, and also has greater area, so that there is a net dipole moment that is suppressed by only 25% in the far field, but close to 100% integrated over the Rx. Details of the coil construction, including the incorporation of a preamplifier in the coil head, are all that have changed in the evolution of the GEM-3.

The architecture of the electronics console (Figure 3) has not changed in a fundamental way, but the actual electronics has been essentially redesigned to take advantage of technology advancements that allow substantial performance enhancements as well as reduced cost.

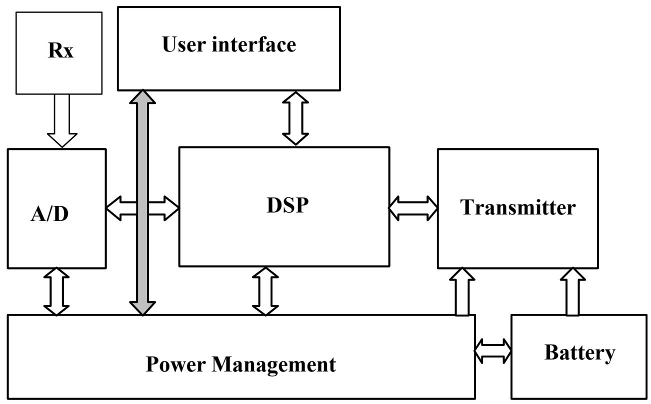


Figure 3. Console block diagram, showing functional modules: receiver front-end (Rx), analog-to-digital converter (A/D), digital signal processor – incorporates on-board memory and removable flash card, transmitter current waveform generator (Tx), and power management – monitors and regulates battery and battery charging and voltages.

Details of the electronics design (including the Tx pulse-width modulation scheme for generating the digitally controlled multi-frequency hybrid current waveform, the front-end analog and analog-to-digital converter (A/D) receiver electronics, digital signal processor (DSP) and flash memory, and power management module) have been submitted to ESTCP in quarterly reports. Although a new custom user-interface was designed and built for the prototype, the full-scale system utilizes a palmtop type computer such as the iPAC™, with custom software for configuring the GEM, and for real-time control and display. The new hardware will also allow the use of a 12V standard off-the-shelf NI-mH battery. A photograph of the electronics is shown in Figure 4.

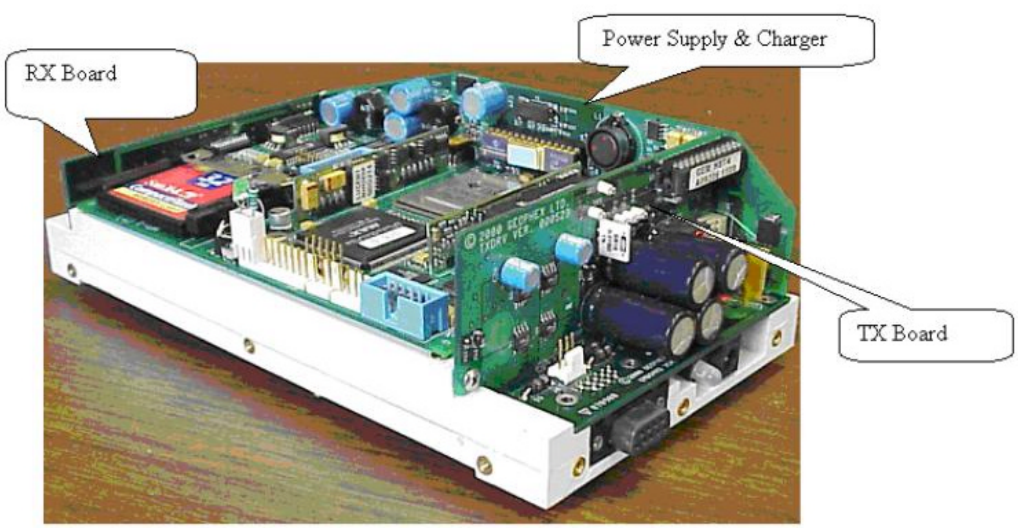


Figure 4. Electronics console, with cover removed, of the enhanced GEM-3.
The DSP and memory with support electronics is on the interior horizontal board.

The method of forming a broadband continuous hybrid current waveform in the Tx (note that most single-frequency systems use an analog tuned resonant transmitter coil and circuit, not appropriate for a multi-frequency system) utilizes a bridge of field effect transistors (FET's), referred to as an H-bridge, that are current gates that can be controlled digitally with software driven logic gates. The arrangement of the gates, drive voltage (12 v), and Tx allows four possible states: open loop (zero voltage with coil open-ended, zero current), +V (full drive voltage supplied to Tx in clockwise sense, current increasing clockwise as/per coil inductance/resistance time constant), -V (full drive voltage supplied in counterclockwise sense, current increasing counterclockwise as/per coil inductance/resistance time constant), and closed loop (Tx shorted, zero voltage, current decaying at inductance/resistance time constant). The first (open) state is only used for time-domain operation or for sequencing arrays (to shut off current as rapidly as possible); the other three states are utilized to shape the current according to a (software) model based on the total Tx circuit inductance and resistance, the drive voltage, and the specified current limit. The temporal pattern of H-bridge switch commands, stored as a series of 2 bits/time interval (referred to as the Tx bit stream) defining which of the four states, is computed by the model during sensor turn-on initialization.

The switching speed of the TX module H-bridge increased from 96kHz to 1.5MHz. By firing the bridge at high speed, the current waveform created by the bit stream in the TX coil will be as close as possible to the theoretical waveform. The high speed switching also results in small charging and discharging steps of the current waveform that will improve the waveform resolution, especially at high frequency range. In order to achieve a smaller time constant in the TX loops, we have changed the characteristics of the TX coils by lowering their inductance and resistance. The H-bridge FET's have lower resistance, reducing the power consumption and heat dissipation.

The new ADC provides 24 bits (increased from 16) at 96 kHz (from 48 kHz), increasing the dynamic range by 48dB and doubling the system operational bandwidth to 48 kHz. The data storage requirement is not impacted because the raw time series data are only temporarily stored until the inphase and quadrature components are computed (i.e. one 30 Hz base period), and there is ample fast-memory capacity available. The DSP has been upgraded so that continuous data can be collected (i.e. up to 30 Hz inphase and quadrature sampling over ten frequencies with single base-period samples; previous GEM-3 DSP required dead-time for inphase and quadrature computations limiting the sampling to under 6 Hz). The flash memory allows data storage of 60 MB data as well as the system software. A photograph of the DSP board is shown in Figure 5. An RS-232 port provides a link to the palmtop user interface or any computer for data transfer, system configuration and control, and a second RS-232 port allows full integration with a DGPS so that stored data will be geo-referenced automatically.

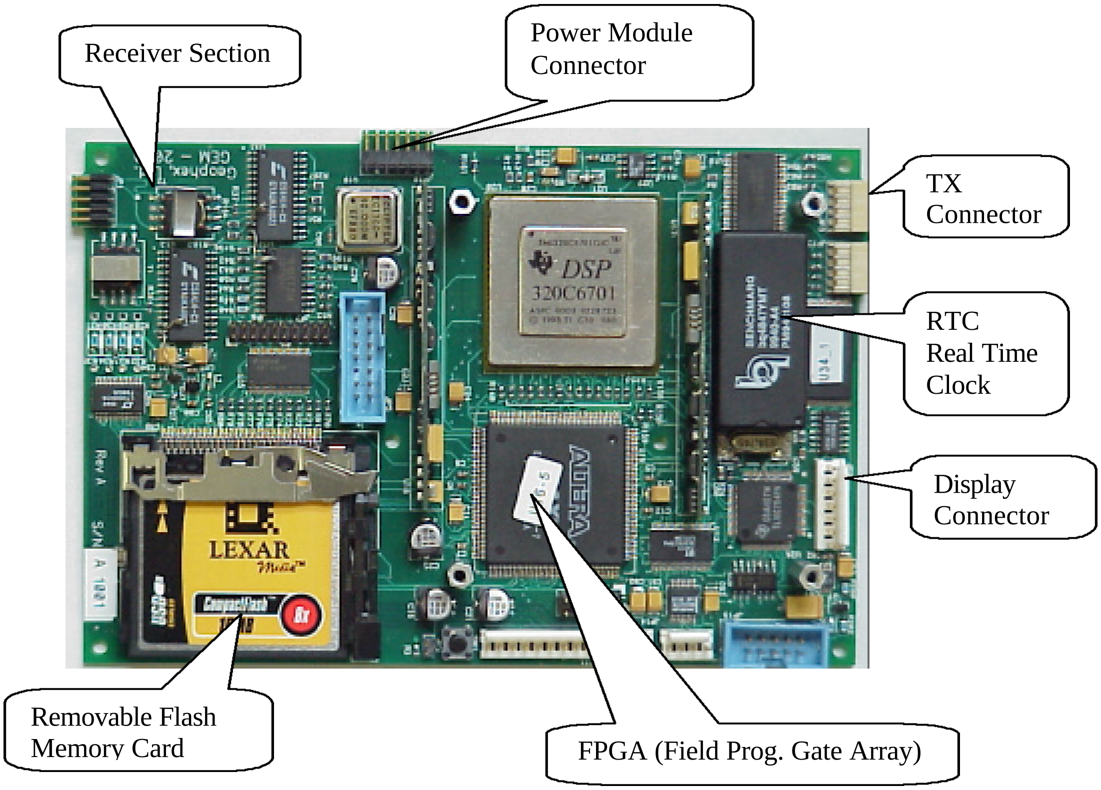


Figure 5. DSP board, showing layout of TI 320C6701 DSP, flash memory, crystal clock, and peripheral support electronics and interfaces to other modules. Fast memory (RAM) resides on backside of card.

2.1.1 Software

The algorithm used for discrimination is a simple fit, with arbitrary weights, to a mix of the two library spectral response modes (transverse and longitudinal) (Norton *et al*., 2001, 2nd). Geometry is not modeled, so data sample positions are not needed, nor target position and orientation. The best-fit library target for a set of samples acquired at the peak of the Response Stage is determined, with goodness of fit as a confidence criteria computed from the fitting error as described above to generate the Discrimination Stage. The algorithm incorporated some modifications under this program following the Kaho'olawe demonstration; the most important allows a frequency-independent offset value for the inphase to desensitize the misfit from soil susceptibility noise (imperfect background removal); also, the data amplitude misfit normalization was modified to decrease the computed percent error for weak targets allowing for weaker s/n.

At Kaho'olawe, the total misfit was computed from a weighted sum at multiple positions, where the weighting was inversely proportional to the distance from the peak response. Data points included were manually selected for each target using a curser selection function built into custom contour mapping software. At the time, we had not yet developed batch-mode software and were evolving our analysis methodology; the manual target-by-target processing was extremely laborious, and the benefit in results not clear, and it is difficult to treat data consistently over the many days of processing required. That motivated the development of an algorithm that could pick target anomalies and perform the ID algorithm and output a dig list with target coordinates, response stage and discrimination stage values, and target ID in a batch mode. The Discrimination Stage for the APG data was computed using this software, with target ID's computed from single points identified with the Response Stage. Use of a single point is much more straightforward for an automated algorithm, and we have not found any benefit from processing multiple samples for the same target in our testing to date, though with more research an optimal method of combining spatial samples without explicit modeling may provide improved classification performance.

The demonstration report will describe hardware and software modifications made to the GEM-3 during the course of this project to achieve the performance attained in the demonstration. Signal/Noise (SNR) benefits will be discussed, as well as usability. Quantitative improvement in SNR during this demonstration is not possible, since the demonstration at the same site has not been performed with pre-existing GEM-3 systems. The Geophex backyard test site was prepared as part of this project, and was not available when we still had old hardware, so we do not have true comparative data suitable for a quantitative s/n comparison. The difficulty in duplicating tests performed with the old hardware where data have been archived is that at the time, s/n analysis was not the objective and the procedures not defined appropriately, and repeating conditions from several years past is difficult, particularly because the dominant noise source at Geophex is local environmental, which is highly variable.

2.2 Previous Testing of the Technology

Initial testing of GEM-3 technology was first performed at the Geophex facility in Raleigh, North Carolina. Geophex has a 10 m x 10 m test bed in which 21 metal pipes of various sizes, some ferrous (steel) and some non-ferrous (3 aluminum, 2 copper), have been buried at depths ranging from 10 to 110 cm depth. We have used this test bed during GEM-3 development to test the performance of each generation of GEM technology. In particular, we tested the current GEM-3, hand-held and cart mounted with DGPS for positioning, on a number of occasions prior to the demonstrations.

The prototype of the full-scale GEM-3 technology was first demonstrated at the Kaho'olawe demonstration in October 2001 for the Naval Explosive Ordnance Disposal Technology Division. The hardware tested incorporated all of the full-scale components except the integrated iPAC™ user interface that has replaced the prototype control and display unit. Minor hardware changes and DSP firmware changes have been made, as well as the system configuration and user-interface (WinGEM) software.

2.3 Factors affecting Cost and Performance

Cost of the technology has decreased from earlier versions of the GEM-3 because of the reduced costs of the electronics components as well as increased utilization of off-the-shelf parts such as the battery and battery charger and the palmtop user interface. The mechanical design will be productionized; the prototype used a hand-made fiberglass/Kevlar boom (hand-held) and cart, and we are now building them from high-strength composite tubes and fittings that are commercially available and require considerably less construction labor as well as reduced materials cost. Production costs of the boards will decrease by numbers of units, with the up-front artwork paid for.

Performance of the technology will be improved from older generations of the GEM-3 as described above. The working environment, such as terrain and vegetation, and the scale of the survey, will affect the cost of field operation of the technology. The operational performance will also depend on these conditions, as well as the mission needs, such as objective target size and depth, and extent and nature of clutter. Also, man-made electromagnetic interference such as power lines, as well as weather conditions, will affect performance.

2.4 Advantages and Limitations of the Technology

The chief advantage of this technology is the potential for discrimination between ordnance and clutter, and/or identification of the ordnance. The broadband multi-frequency data provides maximum EMI information that can be used to identify or classify metal objects. The high sampling rate provides dense coverage when conducting a production survey, and the dynamic range allows detection of small or relatively deep targets while remaining below saturation even when large targets are shallow, or when operating over highly magnetic soil. The various configurations and coil sizes available make the system adaptive to differing conditions (hand-held in trees or over rough terrain, large cart-mounted disk providing increased footprint and depth of exploration for flat open areas).

Other EMI technologies that are suitable for the UXO problem are all time-domain systems (there are only a few candidates), the most common of which provide a single time gate. These single time-gate systems provide little information for discrimination. The newer, more advanced time-domain EMI systems provide a number of time gates that in principle provide information similar to a frequency-domain system, but in order to match the bandwidth of the GEM-3, the decaying transient signal from eddy currents induced in a target must be observed over several decades of decay. Non-EMI technology applicable to UXO detection consists of various forms of magnetometers. Magnetic data provides limited discrimination capability (some capability to estimate size, depth, and possibly aspect ratio), but cannot detect non-ferrous UXO, and is quite sensitive to geology with significant magnetic susceptibility.

Limitations of this technology include the inherent difficulty in distinguishing metal objects by their EMI response; similar size and shaped objects generate similar responses, and even dissimilarly shaped objects may produce similar responses if the depth and orientation is within some particular range. Other limitations include obtaining good signal/noise while surveying over rough terrain, difficulty in surveying in heavy brush or dense forest or steep terrain. Extreme magnetic-soil conditions also degrade data, though not to the point of inoperability. Maintaining adequate spatial coverage while meeting survey production needs over large areas is also a challenge.

3. Demonstration Design

3.1 Performance Objectives

The standard performance metrics for UXO detection/discrimination technology are shown in Table 1. Since the operators will be the demonstrators for this demonstration, Operator acceptance may be interpreted as evaluation by on-site ATC personnel, or their responsible parties in charge of demonstration oversight. Such evaluation can be made by observation of production rates and field problems that arise. The quantitative objectives performance will be determined by ATC resulting from the scoring of the submitted dig sheets.

Type of Performance Objective	Primary Performance Criteria	Expected Performance (metric)	Actual Performance (Objective met?)
qualitative	1.) Ease of use	1.) Operator acceptance	1.) acceptable
	2.) Field worthiness	2.) Operator acceptance	2.) acceptable
quantitative	1.) per cent detected	1.) > 95%	1.) 15%-85%
	2.) false alarms	2.) < .1	2.) .30-.70

Table 1. Performance Objectives

3.2 Selecting Test Sites

Kaho'olawe

The Hawaiian island of Kaho'olawe was used by the military for ordnance testing and as a practice range from World War II to 1993, at which time congress passed a law to return it to the state and to native Hawaiians. The Naval Facilities Engineering Command's Pacific Division (PACDIV) has been given the task of UXO cleanup. To that end, clearing UXO has been ongoing, mostly surface but including subsurface in select areas. Since it is a volcanic island, the magnetic properties of the rock and soil are mostly high susceptibility and remnant magnetization, making use of magnetometers marginally useful for finding buried UXO. A seeded test site has been created in a cleared area in order to test methodologies for buried UXO detection in the geologic environment representative of the island. This site is considered a stringent testing scenario for UXO detection and identification in magnetic geology. Four 30 m x 30 m calibration grids and 22 30 m x 30 m blind test grids were used for this demonstration.

APG

The Aberdeen Proving Ground Standardized UXO Technology Demonstration Site is one of two recently completed facilities designed to provide UXO detection and discrimination technologies test scenarios that evaluate the performance and operational usability under the realistic range of conditions that will be met during assessment and clearance operations. These conditions include various vegetative states from barren to moderate brush to densely wooded and various terrain conditions from open and flat to rugged. These conditions provide opportunity for vehicular towed systems, manual pushcart systems, and hand-held systems. The size of the facility is sufficient to provide meaningful performance metrics such as probability of detection, false alarm rates, and production rates.

The choice of the facility at Aberdeen, in Harford County, Maryland was made for proximity to the operator's location of business (Raleigh, North Carolina), and facility availability.

3.3 Test Site History/Characteristics

Aberdeen Proving Grounds is an Army facility that has been used for weapons and military vehicle testing since 1917. It encompasses 117 km^2 of land, much of it forested, between Baltimore and Philadelphia. The UXO demonstration site is a seeded site for controlled testing, and includes 1) calibration lanes (ground truth revealed) for system training and target characterization, and a set of blind (ground truth withheld) areas for testing a range of scenarios: 2) blind test grid – a 1600 m^2 rectangular grid including access lanes separating 400 discrete 1 m x 1m square interrogation points; 3) open road terrain – large area that can be surveyed with vehicular towed systems, some varied moderately rough terrain and vegetation; 4) moguls – an area with moguls and craters of about ±1 m vertical relief, requiring manual data acquisition, likely hand-held sensor configuration; 5) wooded – various vegetation including significant areas of dense trees.

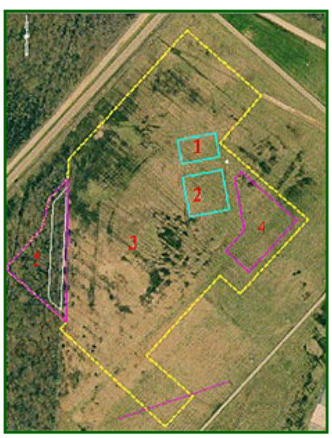


Figure 6. Arial photograph of the APG Standardized UXO Technology Demonstration Site

Both the hand-held and cart mounted systems were tested and "trained" (target libraries collected) in the calibration area. The blind test grid contains 400 actual interrogation squares that will be tested, using the hand-held configuration. The open field will be surveyed with the cart-mounted system at 0.5 m line spacing with DGPS collected by the GEM electronics for geo-referencing the data; all data were stored in the console flash memory and/or the user interface for later processing. The mogul and wooded areas were surveyed with the hand-held configuration in a sweep-search fashion with real-time detection (detection audio signals cue the operator when a metal object is sensed) and identification using two seconds of static data initiated by the operator; detected targets were "flagged" for follow-up geo location, and GEM data will be collected over the target.

3.4 Present Operations

Present operation of the demonstration sites is restricted to controlled testing and performance evaluation of UXO detection and discrimination technologies. It is a cleaned and seeded area with no ongoing operational remediation. At Kaho'olawe, there is extensive ongoing remediation nearby.

3.5 Pre-Demonstration Test and Analysis

There were no specific control tests of other (i.e. operational) technologies prior to this demonstration; other technologies are tested in an ongoing basis for comparative analysis by ESTCP. Pre-demonstration testing of the GEM-3 system utilized the calibration lanes for system training and site/target response characterization. Some samples of UXO were available for system training, and in-air GEM-3 measurements were made with each in two orientations and incorporated into the calibration-lane library data.

3.6 Testing and Evaluation Plan

3.6.1 Demonstration Set-Up and Start-Up

Kaho'olawe

Equipment set-up included assembly of the wheeled pushcarts (two) with the GEM-3 disks and consoles and DGPS rovers, and he DGPS base station. Some ordnance targets were provided for training on site (some had been provided at Geophex prior to mobilization). The first day on site was spent in the calibration/test grids, where ground truth was provided. Data were collected and detected anomalies correlated with ground-truth target locations.

APG

Equipment set-up included assembly of the wheeled pushcart, ATV sled and GEM-3 related hardware mounted on the ATV, including navigation computer, and 48 cm sensor system with mounted electronics console, DGPS and user interface. Similarly, the hand-held systems were assembled, and DGPS interfaced with an iPAC™ for locating the flags. The DGPS base station was initially set up at the USGS reference point, and a rover was used to establish a more convenient reference point near the trailer, for line-of-site radio communication with the mobile units. The systems, including DGPS, were powered up and checked for normal functionality, and ambient noise levels observed. The GEM-3 calibration was verified with a ferrite rod sample target for all systems. Survey lines start/stop points for the pushcart were laid out, as well as lanes for the wooded areas marked with string. The ATV navigation computer was set up with the site boundaries and planned line direction/spacing information.

Initially we used a two-wheeled trailer cart for towing with the ATV, but found this to be somewhat unstable over ruts and gullies and difficult to turn within the safety boundaries. A sled that had been made at Geophex for snow conditions as encountered during the Moguls survey was delivered to the site and replaced the wheeled cart after confirming that it could be pulled over grass with better stability than the wheeled cart.

3.6.2 Period of Operation

The period of operation at Kaho'olawe was October 8- 21, 2001; no work was done on weekends. The period of operation at APG for the Moguls area only was 12/9/02 – 12/13/02, and for the remaining areas, 4/28/03 – 5/7/03.

3.6.3 Area Characterized

The test area at Kaho'olawe included 30 m x 30 m areas designated A-1, A-2, B-1 to 5, through E-1 to 5, totaling 22 sections equal to 1.98 hectares. At APG, all areas including the blind test grid (area 2), open field (area 3), rough mogul scenario (area 4), and the wooded area (area 5) were surveyed, totaling approximately 6.5 hectares. The blind grid was surveyed three times – once with the hand-held sensor, and twice with the 48 cm sensor, statically with the push-cart and dynamically while towing with the ATV.

3.6.4 Residuals Handling

Not applicable.

3.6.5 Operating Parameters for the Technology

Kaho'olawe

The 48 cm radius GEM-3 sensor disk configuration mounted on two-wheeled pushcarts was used for all areas at Kaho'olawe. Ten frequencies were recorded simultaneously: 90, 150, 390, 750, 1470, 2970, 5910, 11910, 23850, 47970Hz, sampled over 1/15 s at 15Hz repetition (i.e. continuous). The carts were pushed at typical walking speeds, with the disk approximately 20 cm height above the ground, along survey lines spaced 0.5 m apart. Two systems were operated simultaneously during most of the survey, with a minimum 30 m separation to avoid interference. Each 30 m x 30 m grid was surveyed between data downloads (initially two areas were surveyed at a time), with about ten minutes time required to download data and change batteries between areas.

APG

Ten frequencies were recorded simultaneously: 90, 210, 390, 750, 1470, 2910, 5850, 11430, 21690, 41010Hz, for all sensors; the 48 cm sensor recorded continuously15 Hz samples, whereas the hand-held operated at 5 Hz continuous sampling (200 ms sample duration). The slight adjustment in frequencies from those at Kaho'olawe were made because, at the lowest end, platform motion induced noise is the major source of noise, and 210 Hz is significantly more immune than 150 Hz (the 90 Hz was retained because it provides important discrimination and is not corrupted by motion for the hand-held mode), and at the high end, 47970 Hz is at the system limit were the sensor response is attenuating and less stable, so the high frequencies were edged down to be well within the system bandwidth. The wheeled-cart mounted disk was about 20 cm height above ground, the ATV towed sled at about 12 cm, and the hand-held was operated 4-7 cm depending on vegetation, water etc. Two hand-held sensors were operated simultaneously during both the Moguls survey (over snow, December 2002) and Wooded area survey (water-covered terrain, April 2003), with a minimum sensor separation of 20 m to avoid interference. We operated the wheeled cart configuration and the ATV towed configuration simultaneously, with 30 m separation required, and also while the wooded area was being surveyed. Nominal line spacing was 0.5 m for the large-disk surveys, and for the hand-held, sweeps were made such that, as best the operator could achieve, the 40 cm diameter disk covered all of the area. Quantifying the gaps while an operator was sweeping was not attempted because there is no practical way to do it, and it depends on the operator.

3.6.6 Experimental Design

Kaho'olawe

Geo-referencing data at Kaho'olawe was completely integrated with the GEM-3 data acquisition, with an RS-232 serial link between the DGPS rover and the GEM electronics console. The DGPS provides position at 1 Hz; the DSP time stamps the 15 Hz GEM data with a clock synchronized to the DGPS time, and also records the time stamped 1 Hz position; WinGEM software interpolates the position to provide UTM referenced GEM data in a single file. Targets were identified from anomalies in the data after completion of the survey and post processing. We first applied a moving median removal (high-pass) filter to all inphase and quadrature ppm data to remove background and sensor offset, and generated quadrature-sum color contour maps for initial target screening. We scrutinized anomalies by manually examining several data channels (i.e. quadrature sum and a low and high frequency inphase) in profile over the anomalies and selected a target list. From that list, we used a software utility in which spatial data around an anomaly are selected with the cursor, and that data passed to one routine that estimates depth, and another that applies the matching algorithm for UXO identification. The matching algorithm executes successively on each point within the selected area, fitting an arbitrary mix of longitudinal and transverse responses to each item in our UXO library. A global misfit is computed from the weighted average, weights based on inverse distance to the center of the anomaly. The confidence (discrimination stage) was determined from the global misfit as well as some subjective assessment of the spatial response of the target.

APG

For the hand-held “sweep-search” mode we utilized sound based on quadrature sum for real-time target detection, and we performed real-time identification immediately after detecting a target. Background removal is performed continuously in real-time; manual initialization (and reset) performed at the operator’s discretion, and continuously updated via recursive low-pass filter with data below a threshold. The data used for identification were recorded with the results in an iPAC, labeled with a flag number marked on flags placed in the ground. The flags were later located with a rover DGPS.

The Blind Grid was surveyed three times: Static data were recorded and processed over the grid square centers with both the hand-held and the wheeled pushcart configurations, and the ATV towed configuration was driven along grid center-lines with data recorded dynamically as in the Open Field survey.

We used sound based on quadrature sum (response stage) to determine if a potential UXO existed in each square for the static scenarios, and if so, we executed the matching algorithm to identify the target, with misfit providing the discrimination stage value via the equation above. Background was computed and subtracted as in the wooded area described above. The data used for the matching and the results (best UXO fit) were recorded in an iPAC.

The ATV test data over the grid were processed with special software designed to look for anomalies (quadrature sum response stage peaks above a threshold) near grid square centers, found via position interpolation from endpoints manually entered for each grid line. The peak response stage data were then processed with the matching algorithm and the discrimination stage computed as/per above equation from the best misfit. Background was removed with a sliding window median filter.

Geo-referencing data over the Open Field was completely integrated with the GEM-3 data acquisition, with an RS-232 serial link between the DGPS rover and the GEM electronics console. The DGPS provides position at 1 Hz; the DSP time stamps the 15 Hz GEM data with a clock synchronized to the DGPS time, and also records the time stamped 1 Hz position; WinGEM software interpolates the position to provide UTM referenced GEM data in a single file. Targets were identified from anomalies in the data after completion of the survey and post processing. The data can be stored in the GEM flash memory and/or in an iPAC; both methods were used, the latter providing a faster means of transferring data to a pc (either USB serial link or flash memory card).

We post-processed the Open Field data (manual pushcart and ATV towed) by first leveling with a moving window median removal filter along the acquisition trajectory for each raw data file, then repackaging the data into files covering 11 spatial blocks. Each of these blocks were processed using batch-mode software that performed several steps as follows: 1) computed the weighted total apparent conductivity which was used as the response stage; 2) identified all points above a prescribed threshold; 3) grouped these into contiguous anomalies along the profile trajectory and selected the peak for each; 4) eliminated single point anomalies; 5) selected the maximum point within a prescribed radius (1.5 m) across parallel profiles and eliminated the others (i.e. reduced multiple anomalies within a 1.5 m circle to a single anomaly); 6) performed the matching algorithm with the GEM spectral data associated with each selected anomaly, providing; 7) estimated the target depth based on anomaly shape; and 8) logged the results, with the best misfit value translated into discrimination stage via the formula above.

The calibration lane was used to generate the matching algorithm library. For that purpose, we collected data over vertical and horizontal orientations of each target; when a target was represented at multiple depths, we sometimes included both (as separate entries) depending on signal strength. The library was augmented with similar data using targets that were provided to us by APG placed on the ground surface.

3.6.7 Sampling Plan

Not applicable.

3.6.8 Demobilization

The GEM-3 technology requires no alteration of the environment and no site restoration was required except for flag removal and lane string removal. All Geophex equipment was be removed at the completion of the demonstration.

3.7 Selection of Analytical/Testing Methods

The analytical/testing method consists of enumeration of UXO detected (i.e. probability of detection (PD)) and non-UXO declared as UXO (i.e. false alarm rate (FAR)). Confidence ranking allows generation of Receiver Operator Characteristics (ROC). Correct UXO identification was also scored.

3.8 Not Applicable

4. Performance Assessment

4.1 Performance Criteria

The performance criteria for the assessment of the technology under demonstration are described in Table 2.

Performance Criteria	Description	Primary or Secondary
Probability of Detection	# UXO detected / # UXO buried	primary
False Alarm Rate	# anomalies not ordnance/m^2	
Reliability	Down time	
Maintenance	Frequency, required training	
Ease of use	Operator productivity	
Factors affecting performance	Operating conditions affecting performance	
Versatility	Other potential applications	secondary

Table 2. Performance Criteria

4.2 Performance Confirmation Methods

Performance confirmation methods include quantitative calculations of PD, FAR, and evaluation of operator hours required to perform the data acquisition (post processing not included). The PD and FAR require ground truth and must be computed by ATC. These may be recomputed as a function of threshold criteria, for generation of ROC curves.

Note that a high P_{fa} for the response stage as a fraction (or %) of (metallic) clutter is desirable, because all metal targets (of sizes/depths comparable to UXO) are intended to be detected, and only in the discrimination stage classified as clutter.

The results of the ATC confirmation are summarized in Table 3 and the ROC curves in Figures 7-12 (ROC curve for Kaho'olawe not available).

Kaho'olawe

Performance Criteria	Expected	Confirmation Method	Actual
Response Stage 1) probability of detection 2) probability of false alarms 3) background alarms	 1) > .90 2) > 90% of total metal targets – UXO 3) < .025/m^2	Government Evaluation	 1) .43 2) .43 3) 547/19800m^2 = .0276/m^2
Discrimination Stage 1) probability of detection 2) probability of false alarms 3) background alarms 4) Efficiency 5) Rejection Ratio	 1) > 80% 2) < .2 (< 20% clutter declared UXO) 3) < .01/m^2 4) .9 5) > 0.5	Government Evaluation	 1) .40 2) .39 3) 496/19800m^2 = .025/m^2 4) .94 5) .07

APG Blind Grid – Hand Held Configuration

Performance Criteria	Expected	Confirmation Method	Actual
Response Stage 1) probability of detection 2) probability of false alarms 3) background alarms	 1) > 95% 2) > 95% of total metal targets – UXO 3) < .01	Government Evaluation	 1) .80 2) .85 3) .30
Discrimination Stage 1) probability of detection 2) probability of false alarms 3) background alarms 4) Efficiency 5) Rejection Ratio	 1) > 85% 2) < .2 (< 20% clutter declared UXO) 3) < .01 4) 0.9 5) > 0.5	Government Evaluation	 1) .60 2) .50 3) .15 4) .76 5) .40

Table 3. Expected Performance and Confirmation Methods (continued below)

APG Blind Grid - 96cm Disk, Push-Cart Mounted Configuration

Performance Criteria	Expected	Confirmation Method	Actual
Response Stage 1) probability of detection 2) probability of false alarms 3) background alarms	1) > 95% 2) > 95% of total metal targets – UXO 3) < .01	Government Evaluation	1) .85 2) .85 3) .40
Discrimination Stage 1) probability of detection 2) probability of false alarms 3) background alarms 4) Efficiency 5) Rejection Ratio	1) > 85% 2) < .2 (< 20% clutter declared UXO) 3) < .01 4) 0.9 5) > 0.5	Government Evaluation	1) .70 2) .70 3) .35 4) .82 5) .19

APG Blind Grid – 96cm Disk, ATV Vehicle Towed Configuration

Performance Criteria	Expected	Confirmation Method	Actual
Response Stage 1) probability of detection 2) probability of false alarms 3) background alarms	1) > 90% 2) > 90% of total metal targets – UXO 3) < .01	Government Evaluation	1) .30 2) .40 3) 0.0
Discrimination Stage 1) probability of detection 2) probability of false alarms 3) background alarms 4) Efficiency 5) Rejection Ratio	1) > 80% 2) < .2 (< 20% clutter declared UXO) 3) < .01 4) 0.9 5) > 0.5	Government Evaluation	1) .20 2) .30 3) 0.0 4) .71 5) .22

Table 3. Expected Performance and Confirmation Methods (cont.)

APG Moguls Area - Hand Held Configuration

Performance Criteria	Expected	Confirmation Method	Actual
Response Stage 1) probability of detection 2) probability of false alarms 3) background alarms	 1) > 90% 2) > 90% of total metal targets – UXO 3) < .01/m^2	Government Evaluation	 1) .15 2) .15 3) .15
Discrimination Stage 1) probability of detection 2) probability of false alarms 3) background alarms 4) Efficiency 5) Rejection Ratio	 1) > 80% 2) < .2 (< 20% clutter declared UXO) 3) < .01/m^2 4) 0.9 5) > 0.5	Government Evaluation	 1) .00 2) .00 3) .05 4) .04 5) .87

APG Woods Area – Hand Held Configuration

Performance Criteria	Expected	Confirmation Method	Actual
Response Stage 1) probability of detection 2) probability of false alarms 3) background alarms	 1) > 90% 2) > 90% of total metal targets – UXO 3) < .01/m^2	Government Evaluation	 1) .25 2) .20 3) .05
Discrimination Stage 1) probability of detection 2) probability of false alarms 3) background alarms 4) Efficiency 5) Rejection Ratio	 1) > 80% 2) < .2 (< 20% clutter declared UXO) 3) < .01/m^2 4) 0.9 5) > 0.5	Government Evaluation	 1) .20 2) .10 3) .05 4) .74 5) .45

Table 3. Expected Performance and Confirmation Methods (cont.)

APG Open Field Area – 96 cm Disk, Pushcart and ATV Towed Configurations

Performance Criteria	Expected	Confirmation Method	Actual
Response Stage 1) probability of detection 2) probability of false alarms 3) background alarms	 1) > 90% 2) > 90% of total metal targets – UXO 3) < .01/m^2	Government Evaluation	 1) .35 2) .30 3) .05
Discrimination Stage 1) probability of detection 2) probability of false alarms 3) background alarms 4) Efficiency 5) Rejection Ratio	 1) > 80% 2) < .2 (< 20% clutter declared UXO) 3) < .01/m^2 4) 0.9 5) > 0.5	Government Evaluation	 1) .25 2) .15 3) 0.0 4) .68 5) .44

Table 3. Expected Performance and Confirmation Methods (cont.)

Performance Criteria	Expected	Confirmation Method	Actual
Reliability	No downtime	Government log	Minor repairs
Maintenance	Battery charging	Government log	~4/day
Ease of use	Minimal training	Operator	Minimal training
Factors affecting performance	Some sensitivity to soil susceptibility and conductivity and target depth	Theory	
Versatility	Other metal detection	Other programs	Underwater UXO

Table 3. Expected Performance and Confirmation Methods (cont.)

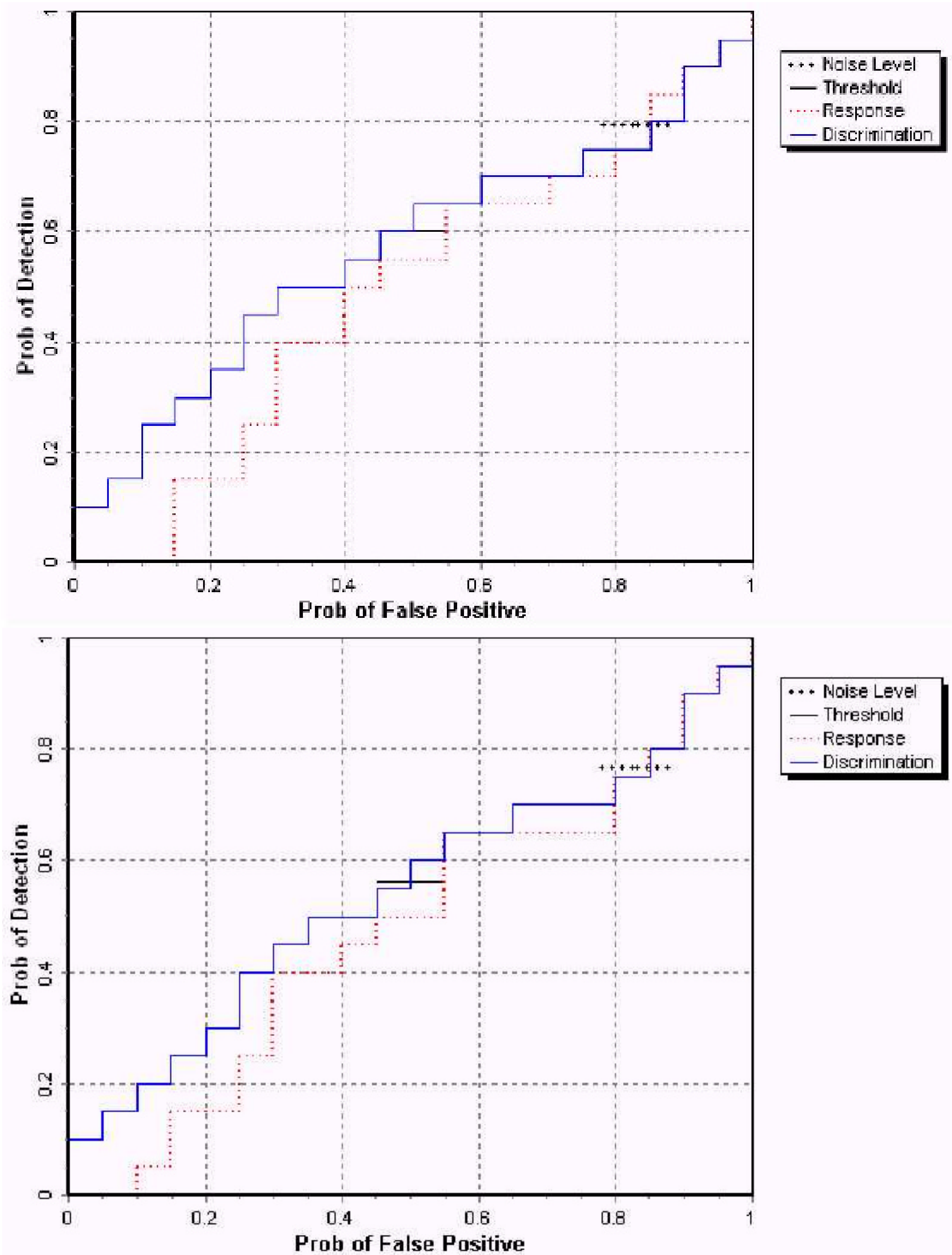


Figure 7. ROC curves for the hand-held configuration over the blind grid; including 20mm ordnance (top), and excluding 20mm (bottom).

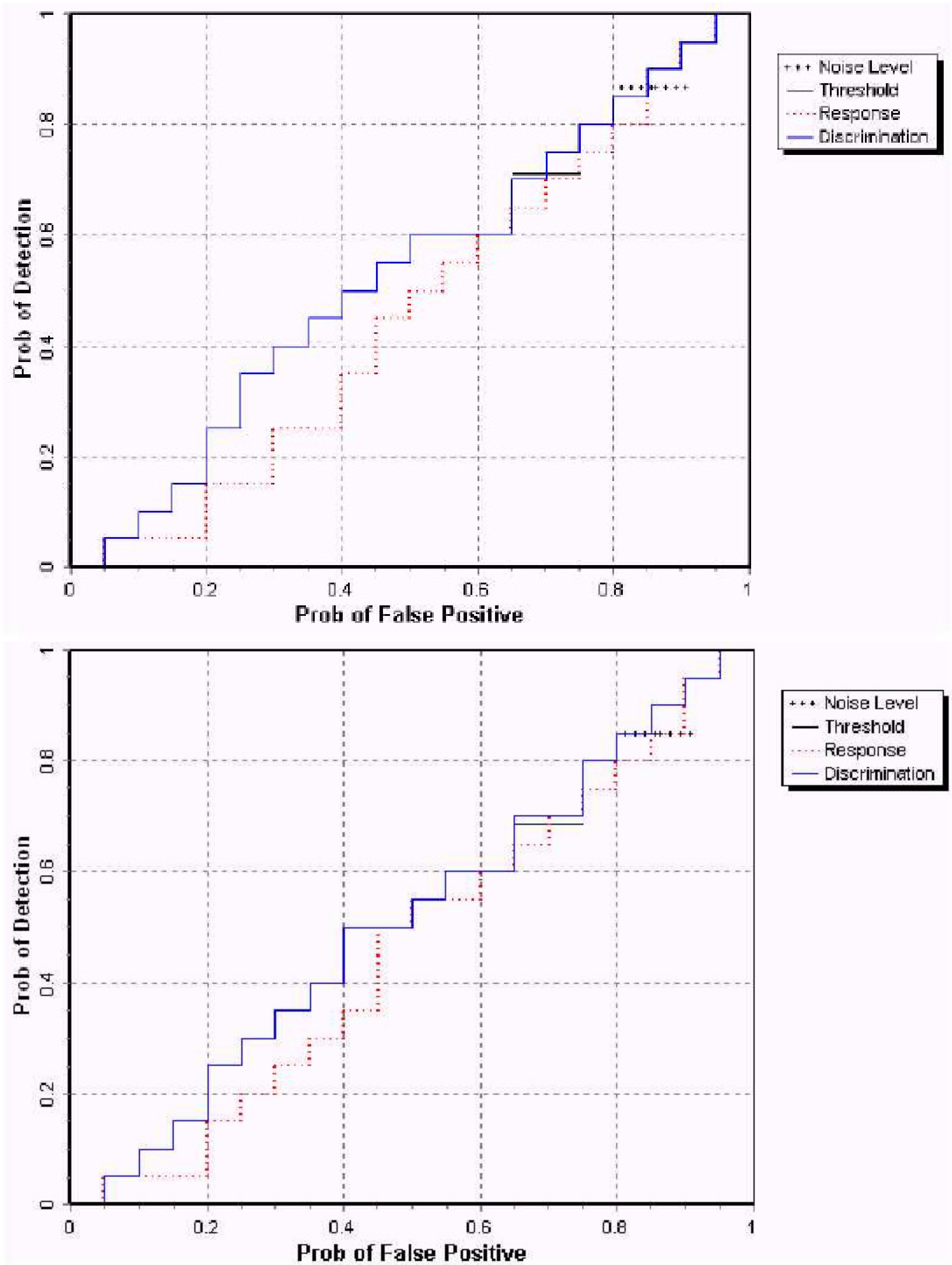
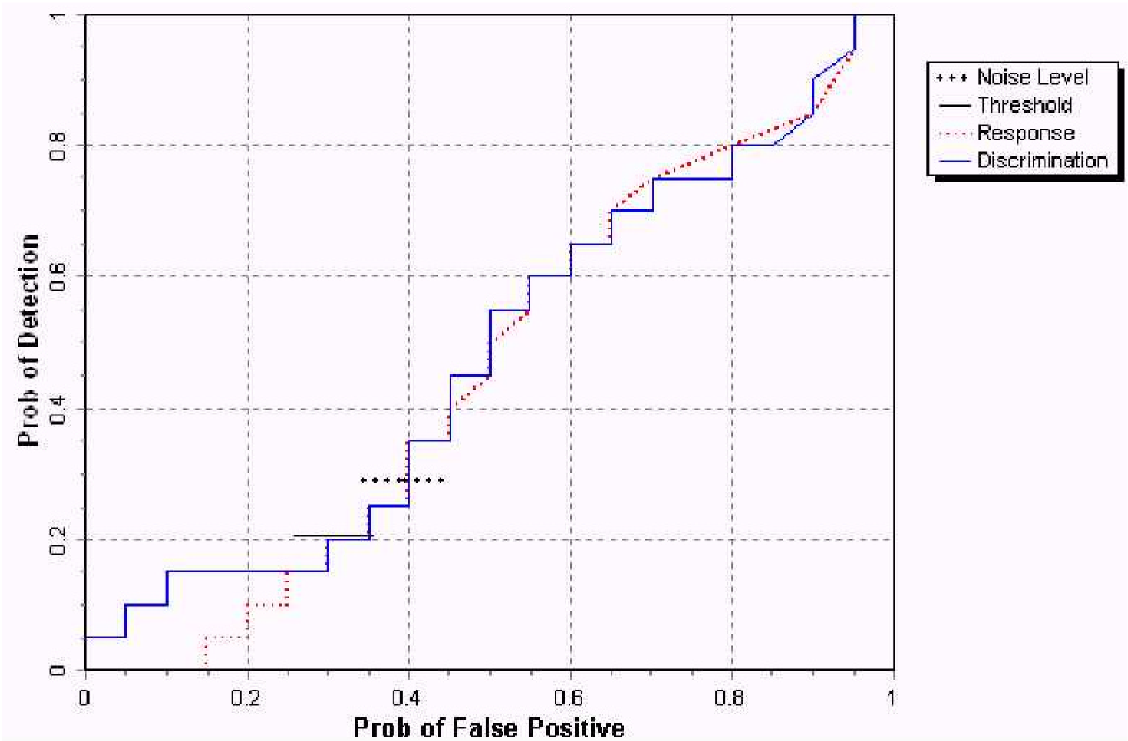


Figure 8. ROC curves for the pushcart configuration over the blind grid; including 20mm ordnance (top), and excluding 20mm (bottom).



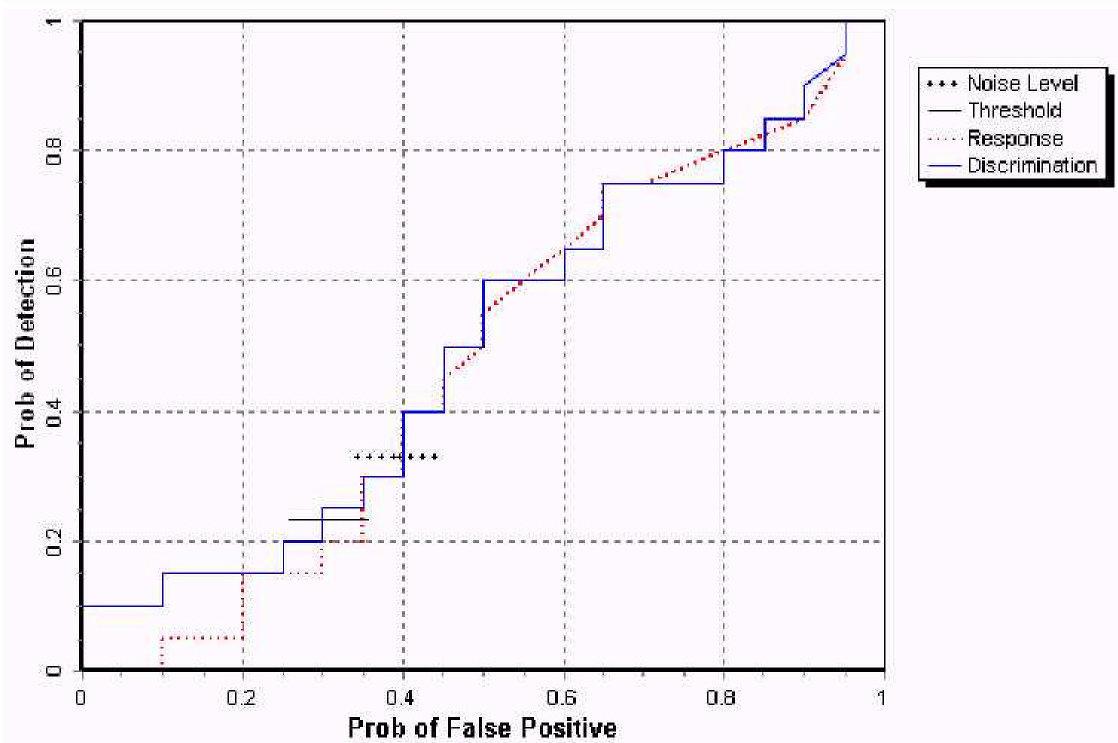
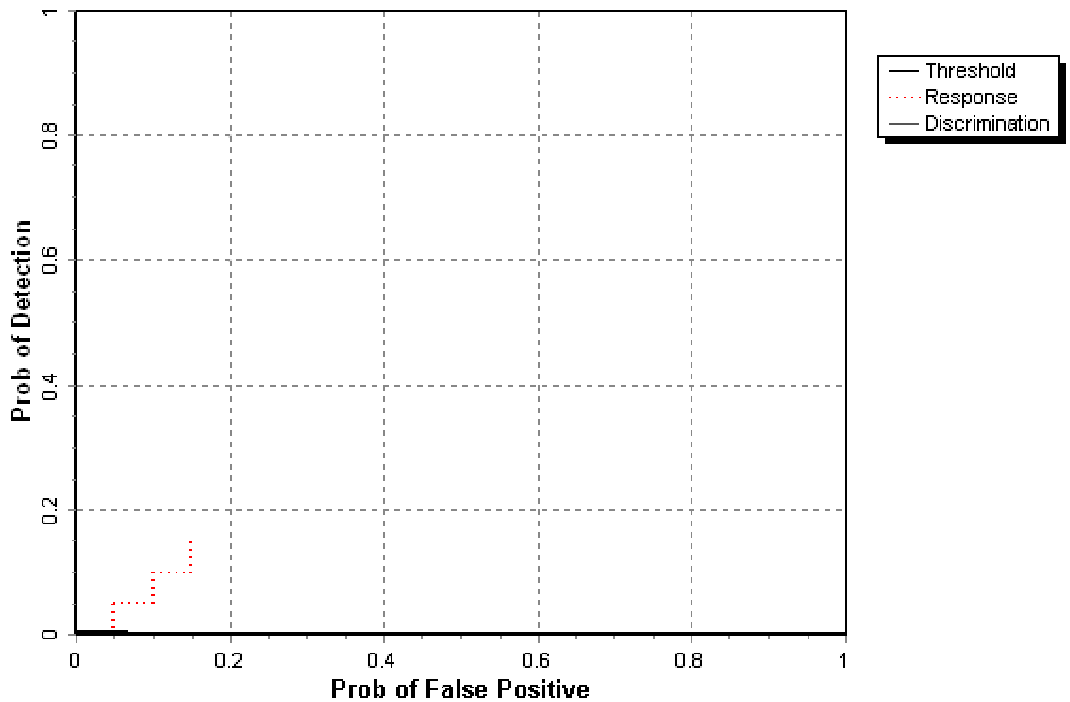


Figure 9. ROC curves for the ATV towed configuration over the blind grid; including 20mm ordnance (top), and excluding 20mm (bottom).



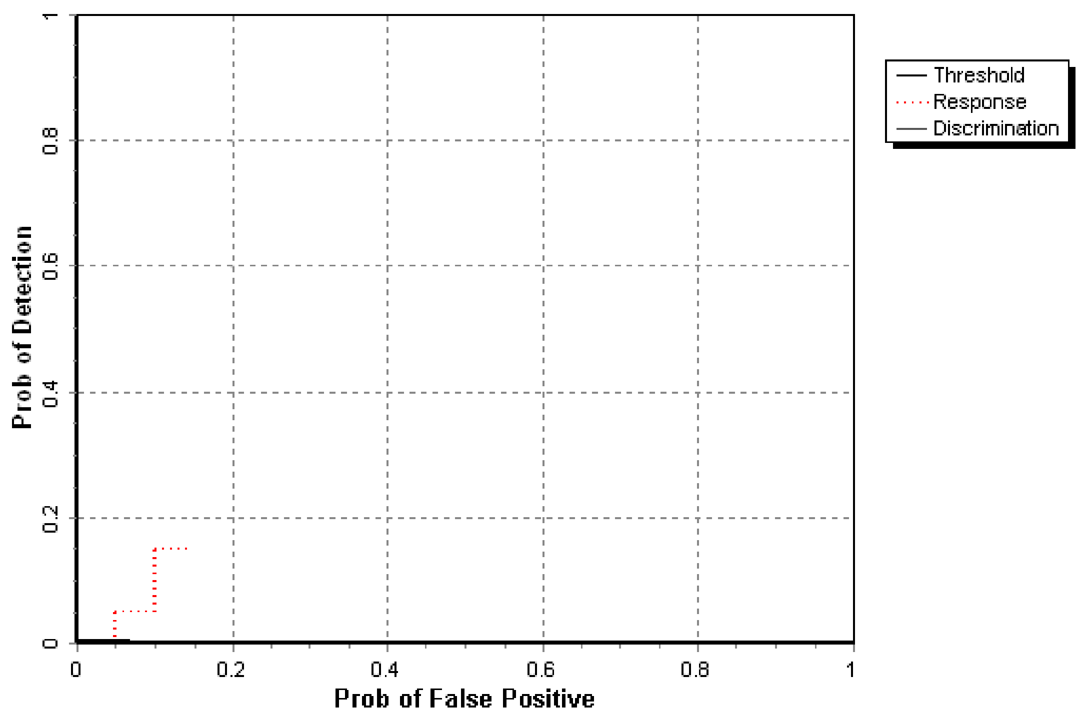


Figure 10. ROC curves for the Hand Held configuration over the open field moguls scenario; including 20mm ordnance (top), and excluding 20mm (bottom).

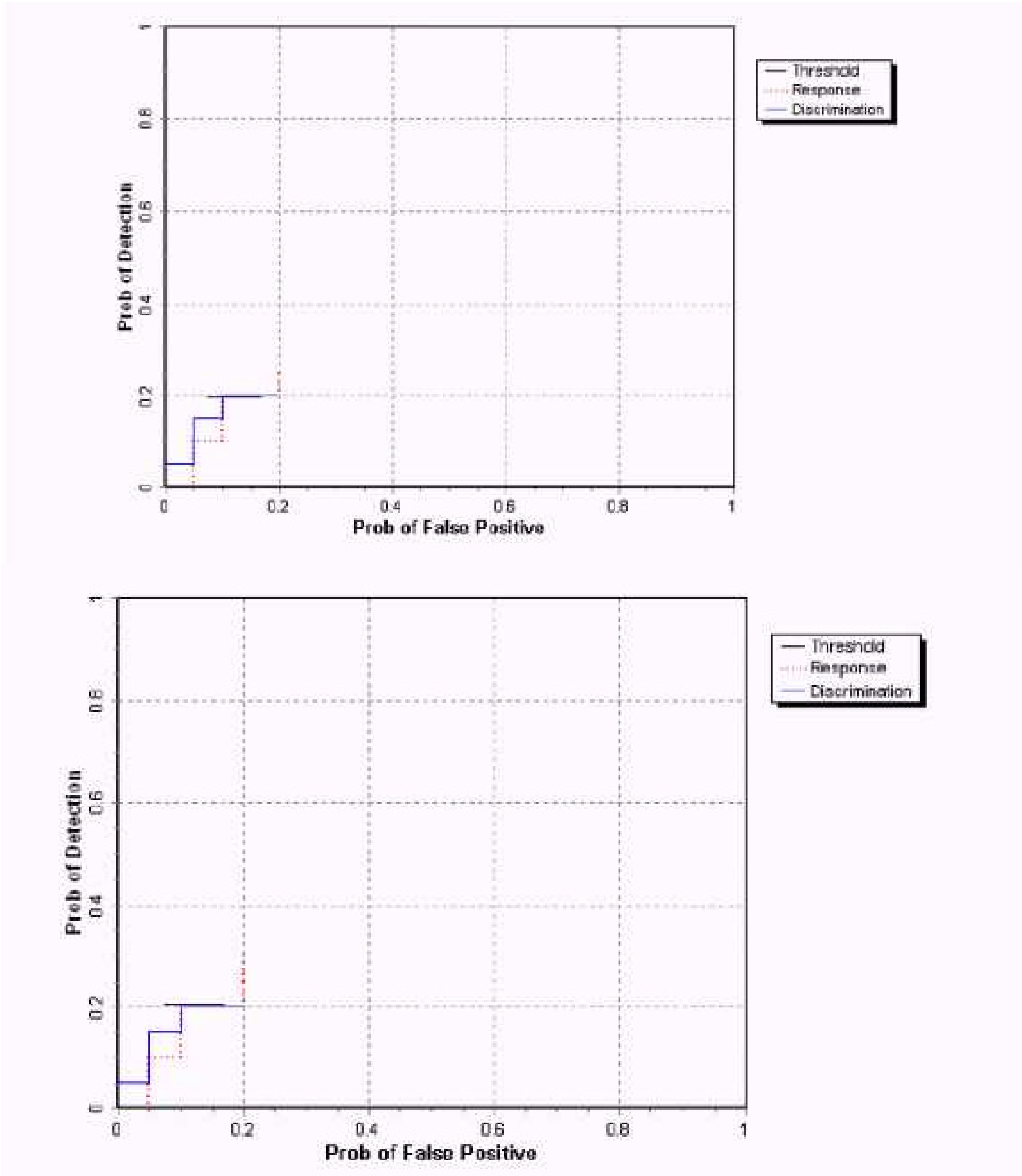
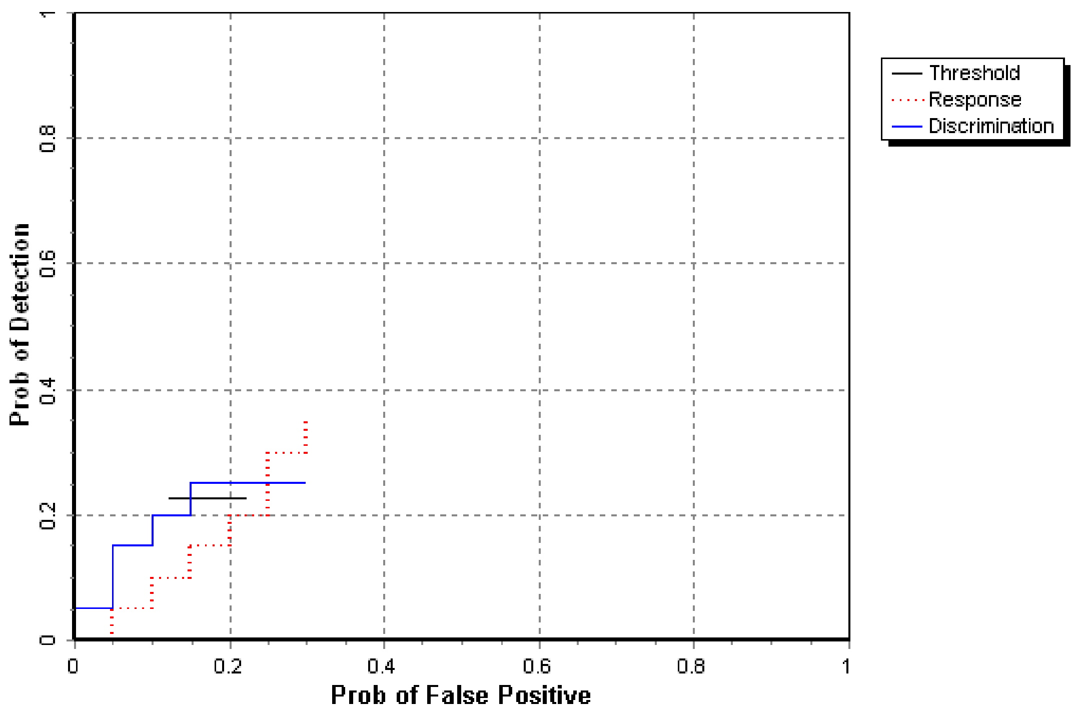


Figure 11. ROC curves for the Hand Held configuration over the open field woods scenario; including 20mm ordnance (top), and excluding 20mm (bottom).



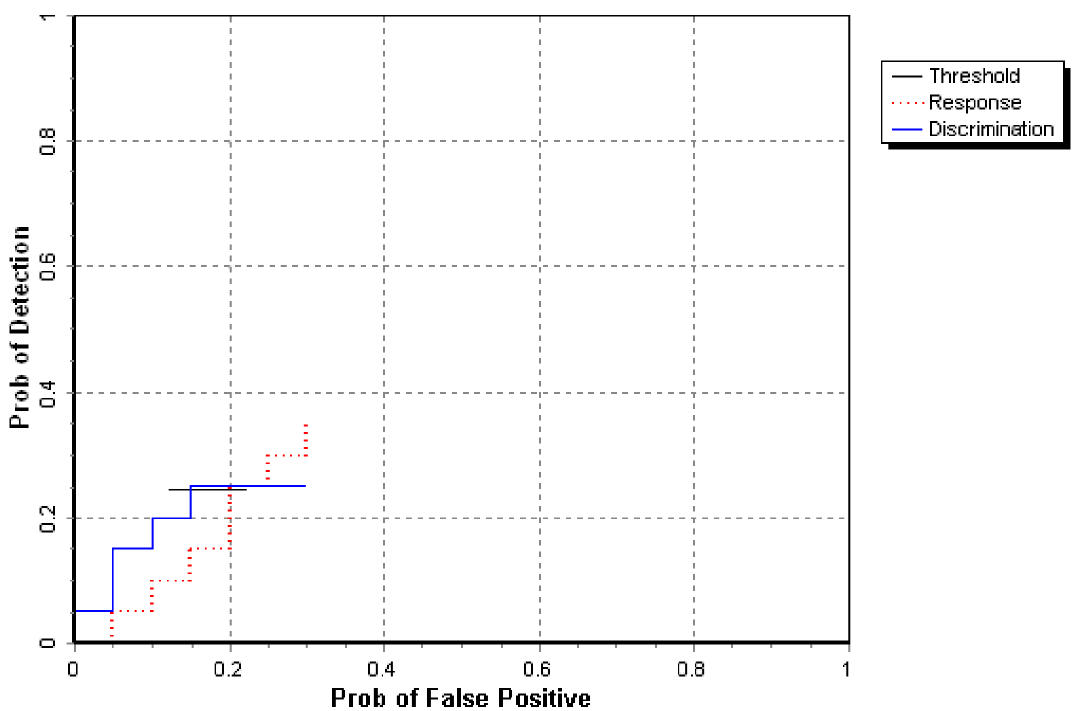


Figure 12. ROC curves for the ATV towed configuration over the open field; including 20mm ordnance (top), and excluding 20mm (bottom).

4.3 Data Analysis, Interpretation and Evaluation

Kaho'olawe

A detailed self-evaluation of the Kaho'olawe demonstration performance was submitted to ESTCP in January 2003; a summary of key points follows.

Of 148 ordnance items not designated non-grade, 91 were detected and declared ordnance with varying confidence but 26 of those were outside the 0.5 m allowed position error radius (but within 1.0 m); there were no data (i.e. an obstacle blocking the cart or surveying error) over 7 of them. Of the 50 ordnance items completely missed and data were available, 14 were 20 mm and 11 were 40 mm items (only 3 of the 20 mm were detected, and 7 of the 40 mm), indicating that the small items were problematic at Kaho'olawe.

Of ordnance declared "non-grade" (not defined in ground-truth tables, but assumed to mean ordnance with missing parts but identifiable), 21 were detected and 4 missed. None of the ordnance (including non-grade) was classified as clutter. Of 158 seeded fragments, 67 were detected, 5 of which were classified as clutter. At Kaho'olawe, our ordnance/clutter threshold was excessively conservative and we thus classified most metal objects as ordnance.

There were a large number of picked targets (547) that did not correspond to seeded or known metal objects, and of these 496 were classified as ordnance, resulting in a very large false background score. However, in there were a number of instances where multiple demonstrators identified the same target, and when followed up with a ground search, a metal object was usually found. Ground follow-up was only undertaken if at least four demonstrators had coinciding targets. We are convinced that a large fraction of our false backgrounds were caused by metal objects, because many were associated with high s/n spectra clearly characteristic of metal (strong quadrature peak below 10 kHz).

Although Kaho'olawe poses a difficult geologic environment, the extreme magnetic geology was not the most important factor in our results. There was no correlation between the level of background susceptibility (which varied significantly) and our performance, and very few features in the processed detection channel obscuring anomalies that could be correlated to magnetic susceptibility.

On the other hand, we found that the low-frequency data (90 Hz and 150 Hz) that are particularly valuable for metallic targets were corrupted by platform motion, which we have since identified as angular motion of the receiver coil in the earth's magnetic field as he cart is rolled over rough ground. We also had navigation errors, both in terms of locating the target within the 0.5 m halo, and in terms of the operator maintaining the 0.5 m line spacing. The latter impacts our ability to find small targets (20 mm and 40 mm) because line gaps ~0.8 m were not uncommon; also, positioning targets from anomalies centered within these gaps is subject to greater error.

APG

Individual scoring reports have been prepared by ATC for each sensor configuration in the blind grid and are being prepared for the mogul, woods, and open areas.

All raw data were provided on a CD, in comma delimited ASCII files, before demobilizing. Raw data consist of inphase and quadrature measurements at each frequency, sampled (integrated) over user selectable multiples of 30 Hz base periods (usually 6 base periods/sample in hand-held mode for an output rate of 5 Hz; usually single or two base periods for survey mode for an output rate of 30 Hz or 15 Hz). Note that in hand-held search mode, data are not recorded except over detected EMI anomalies (significant sound above background). Cart-mounted survey data are recorded continuously.

During "sweep-search" mode, real-time detection and identification was performed, with a goodness-of-fit (i.e. mean absolute error) reported for confidence ranking and clutter classification (discrimination stage). The response stage was indicated by the operator based on audio indication of amplitude. The results were manually logged for generation of dig lists after geo-referencing the targets with DGPS. Data immediately over the target, with background removed, were recorded by the iPAC, and subsequent reprocessing recorded data was an option. The recorded data (spectra over flagged targets) were re-processed to generate dig lists submitted during the 30-day post-survey period; the re-processing provided actual measured response stage values, as well as discrimination stage values converted from the misfit values, and depth estimates.

Following post-processing survey data with target picking and discrimination algorithms, prioritized dig sheets were submitted. These dig lists include grid square identification for the blind grid and UTM coordinates for the other areas, "Response Stage" - detection signal level (i.e., the output above background of the selected detection algorithm, e.g. quadrature sum), Discrimination Stage Ranking – a numerical ranking of likelihood that target is UXO, classification – Empty, Clutter, or Ordnance, Type – ID if ordnance, Depth, Azimuth, and Dip. The last two items were not an output of the discrimination algorithm used.

Hand-held

The performance shown in the tables and ROC curves above did not meet expectations, particularly for the P_d with the hand-held system in the moguls and woods. We believe that a systematic problem with locating the target flags likely resulted in reported position coordinates outside the half meter allowed halo; verbal feedback from ATC indicated that a two-three foot shift in all target positions in the mogul area increased the P_d to about 0.4, still below expectations but more reasonable. A problem with the differential corrections may have occurred, and may not have been exactly the same over the duration of the survey (so that one simple shift of all targets would not achieve the true sensor P_d). These are speculative explanations, and only repeat experiments (planned for spring 2005) can ascertain the hand-held GEM-3 performance.

We detected a very large (~900) number of targets deemed metal objects in the mogul area, and presume that most of them were metallic clutter. Many of them had very strong detection-signal responses; some were weak but considered possible deep UXO. In such a highly cluttered area, it may be that most of the actual UXO were obscured by the clutter responses. Since we do not have information on the number of seeded clutter items, we cannot be fully assured of this conclusion. Similar, though not as extreme, situation occurred in the woods.

The conditions also may have degraded performance – the moguls were snow covered (melting at the end of the survey) with partially frozen pools of water in the gullies, and the woods (April) were swampy with up to 10 inches of water in much of the area. DGPS positioning, though seeming to be functional, probably had reduced accuracy because of tree coverage.

We performed much better in the blind grid, where target location was not an issue. Small shallow targets were detected, classified, and identified better than larger deeper targets. This is in contrast to Kaho'olawe, where in survey mode without guarantee of data directly above the target, they were missed more than larger deeper targets. Although the P_{fa} decreases with the discrimination stage from the response stage, the P_d decreases as well. Discrimination stage provides marginal capability in the low P_d-P_{fa} range, but at acceptable P_d, the discrimination adds no improved performance over the response stage.

Towed and cart pushed 96cm sensor

The performance of the ATV towed system also was well below expectations. This may be attributed to a combination of positioning errors, and data quality issues associated with a sensor towed at ~5 mph along unmarked traverses (some gaps in coverage were evident on the anomaly maps). The nominal half-meter line spacing is difficult to maintain, and improvements in operator queued navigation is needed. Motion-induced noise is also greater in the towed configuration.

In spite of the fact that we posted 765 targets from the response stage and 367 from the discrimination stage, our P_d and P_{fa} were low and P_{ba} was very low, implying the picks were not false positives or false background responses, yet fewer than half the UXO were detected, indicating a high density of objects. Since we did not designate targets with response stages below our threshold, a lower threshold would increase the target dig list, and presumably increase the P_d (though the P_{fa} would increase as well).

In contrast to Kaho'olawe, we did not detect deep targets as well as shallow, but we did detect large targets better than small; at Kaho'olawe there was a correlation between target depth and size that does not appear evident in the APG open area – if larger targets are systematically deeper, then performance trends for size and depth should correlate, but the correlation is reversed. If all target sizes were buried with a similar depth distribution, then independent size and depth performance trends are possible and the open field results make sense – shallower and larger both give stronger responses.

In the blind grid we have a direct compare between static platform and dynamic platform results with the same sensor – 96 cm disk mounted on the push cart where we stopped over each grid point and acquired data for a few seconds, vs. 96 cm disk mounted on sled and towed across the grid with the ATV. The former mode gave results comparable to the hand-held sensor, with slightly better detection of deeper targets and overall slightly higher P_d, with a corresponding slightly higher P_{fa} in the discrimination stage.

The most straightforward method to reduce the motion-induced noise is to increase the transmitter moment. We have demonstrated improvement at low frequencies with the GEM-3 towed array built for the Naval Research Laboratory in which we used a high-power transmitter electronics with up to 48 v into a 10-turn transmitter coil (from our standard 4 turn). We recommend a high-power system for any future towed surveys, driving at reduced speeds, and real-time coverage maps to eliminate any spatial coverage gaps.

Discrimination, based on a simple single-point (spatial) matching algorithm, has not proved to reduce FAR while maintaining P_d except at very high thresholds with associated low P_d. The best discrimination performance occurred with hand-held and pushcart configurations in the blind grid, where data were collected statically over the target. Survey (ATV towed) mode degrades the discrimination performance, and the hand-held in moguls and woods had a systemic problem with target detection/location that rendered discrimination performance invalid.

5. Cost Assessment

5.1 Cost Reporting

Cost reporting consists of tracking production rates for each scenario, mobilization and set-up hours, including hours training over calibration lanes. An itemized cost estimate for the demonstration, produced by ATC based on observer logs, is provided in Table 4 below. Costs for the various scenarios of the demonstration were combined.

	No. People	Hourly Wage	Hours	Cost
Initial Setup				
Supervisor	1	$95.00	8.5	$807.50
Data Analyst	1	$57.00	8.5	$484.50
Field Support	1	$28.50	8.5	$242.25
Subtotal				**$1534.25**
Calibration				
Supervisor	1	$95.00	10.1	$959.50
Data Analyst	1	$57.00	10.1	$575.70
Field Support	1	$28.50	10.1	$287.85
Subtotal				**$1823.05**
Site Survey				
Supervisor	1	$95.00	100	$9500.00
Data Analyst	1	$57.00	100	$5700.00
Field Support	5	$28.50	100	$14250.00
Subtotal				**$16625.00**
Demobilization				
Supervisor	1	$95.00	1.28	$121.60
Data Analyst	1	$57.00	1.28	$729.60
Field Support	1	$28.50	1.28	$36.48
Subtotal				**$887.68**
Total				**$20869.98**

Table 4. Demonstration Costs

5.2 Cost Analysis

The above operational cost for the demonstration is used to estimate operational production costs for an operational mission. Anticipated costs of GEM-3 system and support equipment for purchase and or rental will be estimated.

Initial setup, calibration, demobilization and equipment are based on the premise that both hand-held and towed systems are used, i.e. the mission includes mixed conditions requiring use of both configurations.

Initial setup	Mobilization	$1500
	GEM-3 target training	$1800
Site survey	Data acquisition	$1500/hectare
	Data Analysis	$500/hectare
Demobilization		$800
Equipment Rental	4 Hand-held + towed GEM	$4000/wk

Table 5. Operational Costs Estimate

6. Implementation Issues

6.1 Environmental Checklist

Not Applicable.

6.2 Other Regulatory Issues

Not Applicable.

6.3 End User Issues

Performance, production rates, and costs will be the primary end-user issues; these may vary for different sites and mission objectives.

7. References

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8. Points of Contact

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